*Supporting Information: Additional Methods*

Multi-objective spatial optimization to balance trade-offs between farmland bird diversity and potential agricultural net returns

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# A 1. Farmland bird biodiversity

To represent farmland bird biodiversity, we used a metric representing the aggregate relative abundance of a set of 22 farmland bird species. Further, the metric employs species distribution models (SDMs) representing the potential presence of a species at a given location. We considered all farmland bird species included in the European Farmland Bird Index for the subregions Continental (incl. Eastern Germany) and Atlantic (incl. Western Germany) (PECBMS, 2018). We then added further species that are included in the German national biodiversity indicator species for farmland. From this final list, we excluded species that are not recorded by the Common Breeding Bird Monitoring Scheme of Germany (CBBS) (cf. Kamp et al., 2021). We also excluded the white stork (*Ciconia ciconia*), the common kestrel (*Falco tinnunculus*) and the red kite (*Milvus milvus*) as these are highly mobile species that are not adequately covered by the territory mapping method of the CBBS. Finally, we added the common quail (*Coturnix,* not included in any of the mentioned subsets) as it is a widespread and common farmland bird in Brandenburg and is thus well represented in the dataset.

### A 1.1 Data preparation of bird data and bioclimatic data for the SDMs

We chose two data sources for bird presence for the SDMs: data from the CBBSdataof the Dachverband Deutscher Avifaunisten (DDA, Federation of German Avifaunists) for Brandenburg (Kamp et al., 2021) and the data of the citizen science platform eBird (Sullivan et al., 2009). We included observations of farmland bird presence for the years 2017 and 2018. We filtered the eBird data following Johnston et al. (2021). We included only expert-approved observations with no more than five hours of observation time, no more than 10 observers, and no more than five kilometers of effort distance (i.e., travelling distance). In addition, we selected only protocols of the Travelling or Stationary types. Furthermore, we spatially thinned the complete bird observation points consisting of DDA and eBird data to avoid patterns of spatial autocorrelation. Spatial thinning may prevent an overweighting of the environmental settings of a pixel with more than one bird observation point. If a pixel has more than one observation point, these points would have the same environmental settings, and thus the environmental values of this specific pixel would be overrepresented in the model. To avoid this, we aimed to have a maximum of one observation per grid cell and chose a thinning parameter of 1 km for our 500 x 500-meter grid cells.

For the SDMs, we selected three bioclimatic variables from the BioClim dataset (see Table 4) (Fick & Hijmans, 2017). We excluded all variables concerning the climate in the winter months (e.g., coldest month, coldest quarter) as well as annual temperature ranges and seasonality. We justify this with the fact that only three of the 22 farmland birds are residents, and the rest are migrating birds. The only exception we made here concerned the variable annual precipitation. We included this variable because rainfall does not have an immediate effect on the habitat but is time delayed. The amount of rainfall in winter can affect habitat conditions in other seasons. After this initial step, seven bioclimatic variables were left. We conducted a principal component analysis (PCA) to choose the most important ones from the first four principal components (Table 1), following the approach of Torres et al. (2020). Within the PCA, the three bioclimatic variables listed in Table 2 had the highest variance in our study area, and we therefore included them in the model. We then resampled the raster into a spatial resolution of 500 x 500 meters, which is the basis for all environmental predictor variables in the model. Table 4 provides a complete overview of all variables.

Table 1. Eigenvalues.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | **PC1** | **PC2** | **PC3** | **PC4** | **PC5** | **PC6** | **PC7** |
| Standard Deviation  | 1.873 | 1.7888 | 0.39888 | 0.34475 | 0.11961 | 2.60E-14 | 6.98E-15 |
| Proportion of Variance  | 0.5011 | 0.4571 | 0.02273  | 0.01698  | 0.00204 | 0.00E+00 | 0.00E+00 |
| Cumulative Proportion  | 0.5011 | 0.9583 | 0.98098 | 0.99796 | 1 | 1.00E+00 | 1.00E+00 |

Table 2. PCA loadings; the most contributing variables are highlighted.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **PC1** | **PC2** | **PC3** | **PC4** | **BioClim** | **BioClim Variable Names** |
| 0.335 | -0.429 | 0.061 | -0.266 | bio5 | Max Temperature of Warmest Month |
| 0.348 | -0.421 | 0.16 | -0.076 | bio8 | Mean Temperature of Wettest Quarter |
| 0.348 | -0.421 | 0.16 | -0.076 | bio10 | Mean Temperature of Warmest Quarter |
| -0.501 | -0.101 | 0.08 | -0.845 | bio12 | Annual Precipitation |
| -0.224 | -0.471 | -0.843 | 0.118 | bio13 | Precipitation of Wettest Month |
| -0.415 | -0.338 | 0.337 | 0.308 | bio16 | Precipitation of Wettest Quarter |
| -0.415 | -0.338 | 0.337 | 0.308 | bio18 | Precipitation of Warmest Quarter |

### A 1.2 Model building

For the SDM for the farmland birds in Brandenburg, we used the R Package Wallace (Kass et al., 2018; R Core Team, 2021). First, we used the spatial partition method “checkerboard 1” due to possible sampling bias in the eBird citizen science data and spatial patterns in the environmental predictors. By posing a checkerboard pattern over the whole study area, the “checkerboard 1” method divides the data into two groups depending on where the observations fall on the checkerboard (Radosavljevic & Anderson, 2014). The number of occurrences in each of the two groups therefore differs, and the group formation is less spatially dependent and more random due to the checkerboard pattern. The deviation into two groups seemed suitable for our relatively small number of bird observation points (see Table 3). In addition, we needed a representation of different areas in Brandenburg (e.g., climatic) in each sample because the predictor variables show spatial patterns. The aggregation factor defines the size of the checkerboard fields. We set an aggregation factor of six pixels, which resulted in an area of 9 km2. We set this area size following Wolff et al. (2021), who chose a hexagon grid cell size of 10 km2 for a classification of landscape types in Brandenburg. We parametrized the modeling algorithm Maxent with the tuning parameters “L,” “Q,” “LQ,” and “LQH.” We chose the model with the lowest Akaike information criterion (AIC) and used it to create cloglog-probability maps of occurrence and saved these as well as the response curves for the variables and other accuracy metrics (Phillips et al., 2017a). All models had an AUC > 0.65, which Wallace calculates using the ENMeval R Package (Kass et al., 2021).

Table 3. The number of data points (presences) from the eBird and the CBBS data of the DDA before and after thinning.

|  |  |  |  |
| --- | --- | --- | --- |
| **Thinned** | **Species** | **CBBS** | **eBird** |
| no | Barn Swallow | 70 | 51 |
| yes | Barn Swallow | 70 | 42 |
| no | Common Linnet | 69 | 16 |
| yes | Common Linnet | 69 | 15 |
| no | Common Quail | 13 | 4 |
| yes | Common Quail | 13 | 3 |
| no | Common Starling | 118 | 44 |
| yes | Common Starling | 118 | 41 |
| no | Common Stonechat | 28 | 11 |
| yes | Common Stonechat | 28 | 10 |
| no | Common whitethroat | 67 | 9 |
| yes | Common whitethroat | 66 | 8 |
| no | Corn Bunting | 56 | 21 |
| yes | Corn Bunting | 54 | 20 |
| no | Eurasian Skylark | 101 | 26 |
| yes | Eurasian Skylark | 100 | 25 |
| no | Eurasian Tree Sparrow | 91 | 25 |
| yes | Eurasian Tree Sparrow | 91 | 23 |
| no | European Goldfinch | 91 | 31 |
| yes | European Goldfinch | 91 | 27 |
| no | European Turtle-Dove | 14 | 1 |
| yes | European Turtle-Dove | 14 | 1 |
| no | Fieldfare | 23 | 17 |
| yes | Fieldfare | 23 | 16 |
| no | Lesser Whitethroat | 79 | 13 |
| yes | Lesser Whitethroat | 79 | 13 |
| no | Meadow Pipit | 8 | 5 |
| yes | Meadow Pipit | 8 | 5 |
| no | Northern Lapwing | 9 | 19 |
| yes | Northern Lapwing | 9 | 15 |
| no | Ortolan Bunting | 20 | NA |
| yes | Ortolan Bunting | 19 | NA |
| no | Red-backed Shrike | 84 | 22 |
| yes | Red-backed Shrike | 84 | 18 |
| no | Western Yellow Wagtail | 54 | 12 |
| yes | Western Yellow Wagtail | 53 | 12 |
| no | Whinchat | 33 | 12 |
| yes | Whinchat | 33 | 11 |
| no | White Wagtail | 89 | 42 |
| yes | White Wagtail | 88 | 38 |
| no | Woodlark | 77 | 2 |
| yes | Woodlark | 76 | 2 |
| no | Yellowhammer | 130 | 27 |
| yes | Yellowhammer | 129 | 24 |

### A 1.3 Model variables

For the SDMs, we used the same set of variables for all species. We included only variables that were not changed in the optimization procedure (i.e., share of agricultural land, woody features could not be included). Maxent selects from these variables the most important features using regularization (Merow et al., 2013). Slope and elevation are, for instance, relevant for the common linnet and whinchat, which have preferences for hilly habitats. Distance to water bodies was assumed to be relevant for water-dependent birds, such as the white wagtail. Distance to settlements was assumed to have either positive effects on barn swallow occurrences or negative impacts because it might also be a proxy for domestic cats (Kosicki, 2021). Distance to nature reserves and special protected areas (SPAs) was assumed a potentially important variable for all species due to spillover effects.

Table 4. Model variables.

|  |  |  |  |
| --- | --- | --- | --- |
| **Variable** | **Data source** | **Original datatype** | **Temporal resolution** |
| max temperature of warmest month | BioClim | raster, 30 m resolution | 1970–2000 |
| annual precipitation | BioClim |
| precipitation of wettest month | BioClim |
| slope | DGM200; Datenbestände der Landesvermessungseinrichtungen | raster, 200-m resolution | - |
| elevation | DGM200; Datenbestände der Landesvermessungseinrichtungen | raster, 200-m resolution | - |
| distance to water bodies | Weigand et al. (2020) | 10-m resolution | 2018 |
| distance to settlements | Weigand et al. (2020) | 10-m resolution | 2018 |
| distance to nature reserve (Naturschutzgebiete) | state office for the environment of Brandenburg | vector data, polygons | - |
| distance to SPAs | state office for the environment of Brandenburg | vector data, polygons | - |
| distance to forest | Weigand et al. (2020) | 10-m resolution | 2018 |
| distance to solar plants | state office for the environment of Brandenburg | vector, point data  | 2021 |
| distance to windparks | state office for the environment of Brandenburg | vector, point data  | 2021/04 |
| farmland bird occurrence | eBird, CBBS | vector, point data | 2017, 2018 |

The forest class comprises the high seasonal vegetation and the high perennial vegetation class from Weigand et al. (2020). The small woody features were taken from Blickensdörfer et al. (2022), who mapped crop types in Germany for 2017, 2018, and 2019 as well as small woody features (SWF). Their SWF class was trained on the SWF High Resolution Layer (HRSL) provided by the Copernicus land monitoring service (EEA, 2019). The minimum mapping unit is 0.5 ha. To avoid confusion with forest, they used an agricultural land mask based on a digital landscape model of 2018, which is part of the official topographic-cartographic information system and provided by the German Federal Agency for Cartography and Geodesy (further information can be found in Blickensdörfer et al., 2022). We considered SWF only if it was classified in two of the three years as SWF.

These two products differ spatially from each other, but there might be a spatial overlap between the two if Weigand et al. (2020) classified an area as high seasonal or perennial vegetation that is located within the agricultural land mask used by Blickensdörfer et al. (2022). The spatial overlap is relatively small.

### A 1.4 Relative abundance and farmland bird biodiversity indicator

To represent farmland bird diversity, we used an index representing the aggregate relative abundance of the selected set of 22 farmland bird species as well as the probability of their occurrence. Specifically, the metric consists of the cloglog-probability maps described in A1.2 as well as the relative abundance values per landscape and bird species (see Table 5). To estimate the relative abundance of birds, we used the initial landscape map and the high-quality CBBS data (Kamp et al., 2021). We averaged the abundance per species and landscape and converted them into relative abundance measures (1 = highest) to ensure comparability across species, with a score of 1 representing the highest abundance of each species seen across the landscape (Law et al., 2021). More precisely, we divided the aggregated abundance per species and landscape by the maximum aggregated value of that species, thus assigning the landscape type with the highest overall abundance the value of one. The objective function for farmland bird biodiversity employs both relative abundance and the SDMs. By summing the multiplied relative abundance with the occurrence probability (cloglog map) from the SDMs, given the initial landscape map for 2018, we obtained a farmland bird biodiversity map (Figure S1) (Phillips et al., 2017b). This can be done for any solution obtained from the optimization as well.



Figure S1. Farmland bird diversity map for the initial landscape map and the 22 bird species described in detail below. The theoretical maximum is 22.

### A 1.5 Relative abundance

The following table with the relative abundances per species and landscape is based on the data from the Common Breeding Bird Survey as well as on our agricultural landscape map (Kamp et al., 2021).

Table 5. Relative abundance for our set of 22 farmland birds.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Species | Small fields, few woody features | Small fields, many woody features | Large fields, few woody features | Small fields, moderate number of woody features | Forest | Urban | Water | Grassland | Other |
| White Wagtail | 0.61 | 0.91 | 0.28 | 0.93 | 0.25 | 0.76 | 0 | 0,69 | 0.35 |
| Common Linnet | 0.52 | 0.17 | 0.46 | 0.81 | 0.12 | 1 | 0.38 | 0.48 | 0.18 |
| Whinchat | 0.13 | 0.3 | 0.11 | 0.22 | 0.16 | 0 | 0 | 1 | 0.02 |
| Common Whitethroat | 0.47 | 0.31 | 0.41 | 0.62 | 0.06 | 0.33 | 1 | 0.29 | 0.34 |
| Eurasian Skylark | 0.82 | 0.38 | 1 | 0.71 | 0.11 | 0.04 | 0.1 | 0.71 | 0.12 |
| Eurasian Tree Sparrow | 0.59 | 0.4 | 0.22 | 0.46 | 0.11 | 1 | 0 | 0.31 | 0.17 |
| Yellowhammer | 0.56 | 1 | 0.51 | 0.8 | 0.34 | 0.09 | 0.36 | 0.62 | 0.76 |
| Corn Bunting | 0.93 | 0.49 | 0.91 | 0.81 | 0.16 | 0.08 | 0 | 0.94 | 0.32 |
| Woodlark | 0.21 | 0.16 | 0.19 | 0.14 | 0.31 | 0.05 | 0.43 | 0.08 | 1 |
| Northern Lapwing | 0.28 | 0.33 | 0.46 | 0.56 | 0.04 | 0 | 0 | 0.85 | 0.26 |
| Lesser Whitethroat | 0.37 | 0.42 | 0.29 | 0.4 | 0.12 | 1 | 0 | 0.27 | 0.23 |
| Red-backed Shrike | 0.3 | 0.23 | 0.28 | 0.42 | 0.17 | 0.02 | 0.85 | 0.58 | 0.51 |
| Ortolan Bunting | 0.81 | 0.63 | 0.39 | 0.92 | 0.01 | 0.24 | 0 | 0.34 | 0 |
| Barn Swallow | 0.51 | 1 | 0.14 | 0.51 | 0.07 | 0.23 | 0 | 0.35 | 0.03 |
| Common Stonechat | 0.77 | 0.45 | 0.16 | 0.68 | 0.09 | 0.12 | 0.33 | 0.65 | 0.16 |
| Common Starling | 0.39 | 0.36 | 0.08 | 0.44 | 0.2 | 1 | 0.02 | 0.45 | 0.41 |
| European Goldfinch | 0.55 | 0.54 | 0.36 | 0.82 | 0.16 | 0.71 | 0 | 0.93 | 0.56 |
| European Turtle-Dove | 0.08 | 0 | 0.18 | 0.06 | 0.31 | 0 | 0 | 0 | 1 |
| Fieldfare | 0.18 | 0.67 | 0.41 | 0.48 | 0.25 | 0 | 0 | 0.46 | 0.22 |
| Common Quail | 0.39 | 0 | 0.88 | 0.67 | 0.09 | 0.28 | 0 | 0.51 | 0 |
| Meadow Pipit | 0.09 | 0 | 0 | 0.03 | 0.03 | 0 | 0 | 1 | 0 |
| Western Yellow Wagtail | 0.61 | 0.03 | 1 | 0.48 | 0.02 | 0.02 | 0 | 0.32 | 0.01 |

### A 1.6 Detailed information on the selected open- and farmland birds

The following bird species accounts are based on population trends of common breeding birds in Germany 1990–2018 (Kamp et al., 2021), Kosmos Vogelführer (Svensson et al., 2017), the IUCN Red List (*IUCN Red List of Threatened Species*, n.d.), and the red list for Brandenburg (Landesamt für Umwelt (LfU), 2019).

| **Species** | **Habitat** | **Systems** | **Nest site** | **Wintering** | **Diet** | **Breeding** | **Population Germany** | **Population Brandenburg** | **Population worldwide** | **Red list**  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| White Wagtail / *Motacilla alba* | settlements, wide variety of non-forested wet and dry habitats (lakeshores, riverbanks farmland, garden, parks and short grass), open (cultivated) area | terrestrial, freshwater | buildings, hole or crevice in a riverbank, walls, bridges, woodpiles | Mediterranean (here residents) or northern Africa, in Germany present from March to Octobre | insectivorous, wide range of small terrestrial and aquatic invertebrates, fish fry, crumbs and other household scraps | Breeding period April to August, monogamous species | common | not mentioned on red list of Brandenburg 2019 | current population trend is stable, 25% of global range lives in Europe, occurs all over Europe and Russia and Asia, Middle East and Northern Africa | least concern |
| Common Linnet / *Linaria cannabina* | lowland open heaths, broom, Juniper and commons, moorlands, hills with scattered trees, valleys with low shrubs, alpine meadows, mountain slope, open rocky hillsides, woodland, forest clearings and edges, orchards, plantations,gardens, edeges of cultivation | terrestrial  | shrubs, low in dense bush or shrubs (thorn bush) or hedge or coniferous saplings  | Mediterranean  | seeds, buds (Knospen/Keime), some invertebrates | Breeding period mid-April to early August | common | category 3: endangered | Current population trend is decreasing due to intensification of agriculture and loss of hedgerows and fallow fields, 65 % of population lives in Europe, occurs in Europe (but not Northern Scandinavia and Island), part of Russia, part of the middle East, the very Northern Africa (only small stripe) | least concern, but decreasing population trend |
| Whinchat / *Saxicola rubetra* | farmland, wet meadows, pastures, bogs, heath, bracken-covered hillsides (Farnkraut), dry or wet shrublands, edge of reedbed (Schilf), requires scattered trees or shrubs but also herbs and bare soil | terrestrial | ground-level | Afrotropics | insectivorous, invertebrates mainly, fruits, seeds | Breeding period mid-April to early August | less common | category 2: strongly at risk | Current population trend is decreasing due to intensification of agriculture and harvesting dates, 75 % of population lives in Europe | least concern, but decreasing population trend |
| Common Whitethroat / *Sylvia communis* | farmland, open country in wide variety of landscapes, mostly scattered bushes and shrubs close to grassy patches | terrestrial | shrubs, bushy terrain and open landscape with hedges, plantation clearings, orchards, hedgerows along roads or railway lines, shrubs near watecourses, steppes, hedges around field crops especially cereals | Sahel-Sudan, south of the Sahara, in Germany present from April to September | insectivorous, insects but in late summer fruit uptake increases and in autumn winter it feeds mainly on berries | Breeding period April to July | common | category prewarning  | lives in Europe and European Russia, population is estimated to be stable in Europe, threats are intensification of agriculture with destruction of hedgerows and bushes  | least concern |
| Eurasian Skylark / *Alauda arvensis* | farmland, open habitat, farmland, heathland, moorland, meadows, grassland, steppe, edges of marshes and dunes, extensive forest clearings; avoids wooded areas and xeric (trockene) habitats | Terrestrial, freshwater, marine | ground-level, excavated scrape or natural depression among short vegetation | Westpalearctic | insectivorous, invertebrates, seeds, other plant material, seasonal diet: summer = insects, winter = herbivorous | Breeding late March to August and September | abundant | category 3: endangered | occurs in Europe (30% of the global range), Russia, parts of Asia, middle East, parts of Australia, New Zealand, USA, Canada. Population trend decreasing due to agricultural intensification (changes in management of cereal-growing and grassland -> reduced nesting and foraging opportunities, less food resources, heavy fertilizer, pesticied and herbicide usage makes grasslands gow too tall for nesting.) | least concern. but decreasing population trend, advised: leaving stubble fields over winter, reductions in use of fertilizer, maintenance of crop diversity |
| Eurasian Tree Sparrow / *Passer montanus* | farmland, cultivated areas with hedgerow trees, orchards, gardens and farmyards, less commonly in light woodland, in the east found in built-up areas, open arid country | Terrestrial | trees, open woodland near cultivated areas or settlements, hole in a tree/earth bank/ artificial structure | Resident | granivorous, prefers smaller seeds of low herbs and grasses (cultivated cereals included), animal food | Breeding in the north of its range starts in April or May | abundant | category prewarning  | occurs in Europe (25% of the global range), middle East, Russia, Asia northern of Himalaya, South East Asia, some areas in Australia and USA, threatened by increased use of herbicides/pesticides, autumn sowing of cereals in Europe | least concern, but decreasing population trend |
| Yellowhammer / *Emberiza citrinella* | farmland, farmland, edge of forests, clearings, heathland, coasts with single trees or bushes, transition zone between woodland and open country: Farmland with hedges, forest clearings, young plantations, scrubs, heath, natural grassland | Terrestrial | ground-level, field boundaries or ditches hidden among the vegetation, hedges or isolated bushes | Westpalearctic | insectivorous, seeds and other plant material | Breeding starts in April and late broods may even start in September | abundant | not mentioned on red list of Brandenburg 2019 | occurs in most of Europe (60% of global range), European Russia, parts of the middle East, parts of Australia and New Zealand, threatened by habitat distruction and reduction in cultivation of cereal crops | least concern but decreasing population trend |
| Corn Bunting / *Emberiza calandra* | farmland, open rolling grasslands, tolerates scattered bushes but no dense bush cover, needs elevated vantage points for singing like single trees or bushes or fence posts | Terrestrial | ground-level, hidden among vegetation | Westpalearctic | insectivorous, plant seeds,  | Breeding starts in late May | less common | not mentioned on red list of Brandenburg 2019 | Europe (20% of gloabl range), middle east, northern africa, threatened by the industrialization of agriculture | least concern, moderate decline in Europe |
| Woodlark / *Lullula arborea* | open forests (prefers pine forests on sandy soils or mixed and decidious forests with clearings, heathlands), low intensity/ abandoned farmland, heathland, young forestry plantations, orchards, woodland edges, parkland | Terrestrial | ground-level, depression in the ground sheltered by a bush or tree stump | Atlantic | insectivorous | Breeding from March to July | less common | category prewarning  | Europe (90% of global range), Western Russia, Northern middle East | least concern, increasing population trend |
| Northern Lapwing / *Vanellus vanellus* | Wet natural grasslands, meadows, hay meadows with short swards and patches of bare soil, low altitudes (<1m), grassy moors, swampy heaths, bogs, arable fields, close to water | Terrestrial, Marine | ground-level, shallow scrape in short grass vegetation | Atlantic | invertebrates, insects, snails, earthworms, frogs | Breeding from April to July | common | category 2: strongly at risk | Europe, Russia, parts of Asia, middle East | Near Threatened, decreasing population trend (due to changing of agricultural practices, wetland drainage, intensifictaion) |
| Lesser Whitethroat / *Sylvia curruca* | open country or near forests, shrubland, hedgerows, plantations with small trees, gardens, parks | Terrestrial, Freshwater | shrubs or tree, occasionally in herbal vegetation | Sahel-Sudan  | insectivrous, fruits | Breeding from late April to early August | common | not mentioned on red list of Brandenburg 2019 | Most of Europe (45 % of global range), Russia and parts of Asia, thw whole middle East including Saudi Arabia, southern of the Sahara | Least concern, stable population trend |
| Red-backed Shrike / *Lanius collurio* | open cultivated country hedges and dornshrub, gently sloping terrain, mosaic-like grassy vegetation and bare areas, scrub along railways and roadsides, forest clearings | Terrestrial, Freshwater | shrubs, often thorny bushes | Sub-Sahel | insectivorous | Breeding from May to July | common | category 3: endangered | Most of Europe (60% of global range), parts of Russia, Turkey, East-Southern Africa | Least concern, but declining population trend |
| Ortolan Bunting / *Emberiza hortulana* | continental climate habitat with many hours of sunshine and low rainfall, low intensity mixed farmland, scattered trees or bushes, forest cleaings | Terrestrial | ground-level, often in a field of growing crops | northern sub-Saharan Africa | invertebrates and seeds | Breeding from mid-April until early June | n.a. | category 3: endangered | parts of Europe (80% of ist range): Eastern Europe, southern France, Italy and parts of Spain, Sweden and Finland, Turkey and parts of Russia, small patches in sub-Saharan Africa | least concern, bur decreasing population trend |
| Barn Swallow / *Hirundo rustica* | settlements, wide range of climates and over wide altitudinal range, open country such as farmland with water nearby, towns and cities | Terrestrial, Freshwater | buildings | Afrotropics, South America, South of Asia | insects | Breeding from May to August | common | category prewarning  | Europe (20% of global range), Russia, Asia, South East Asia, North America, South America, southern Africa | least concern, but decreasing population trend due to intensification of agriculture |
| Common Stonechat / *Saxicola rubicola* | open habitat, open usually rather barren landscape, open scrubby country, shrubs and/or human-made structures (stone walls, fence posts, uneven herb rich substrates, alpine moorland, heathland, grassy hillsides, dry plains, bush-studded pastures, woodland edge, sandy forest clearings, field margins and fallows, wide shrubby riverbeds, open garrigue with Cistus, unkempt marshy areas, swamp fringes, roadsides and railway margins and vineyards | Terrestrial, Freshwater | ground-level, well hidden at base of tuft of herbage or under a small bush | Mediterranean | insectivorous, invertebrates, insects and their larvae, occasionally small vertebrates, seeds and fruit | March to mid-August | less common | not mentioned on red list of Brandenburg 2019 | occurs in Europe (20% of global range) but not in Northern countries ( Scandinavia), Russia and Asia, Middle East and parts of Africa (North and South) | Least concern, stable population trend |
| Common Starling / *Sturnus vulgaris* | farmland, open country, woodland or human-made structures for nest sites, open areas of short grassland for foraging, moorland, saltmarshes, seashore, stubble fields, orchards | Terrestrial, Marine | trees, hole in a tree, cliff, building or other structure, nestboxes | Westpalearctic | invertebrates, omnivorous: animal and plant material all year round | March to July | abundant | not mentioned on red list of Brandenburg 2019 | occurs in the whole of Europe (55% of global range), parts of Russia and Asia, middle East, introduced in North America, South Africa, Australia | Least concern, but declining population trend |
| European Goldfinch / *Carduelis carduelis* | several, open or sparse deciduous woodland and mixed deciduous coniferous woodlands, forest edges, heaths, hedgerows, streams, marshy areas with bushes and trees, steppe grasslands with scattered trees, edges of cultivation and parks and gardens | Terrestrial, Freshwater | trees | Meditarranean | granivorous , seeds, buds flowers and plant fruits | April to early August | common | not mentioned on red list of Brandenburg 2019 | Occurs in Europe (55% of global range) but not northern Scandinavia, parts of middle East, Western Russia, North Africa, Australia. Theratened by trapping and kept as cagebird (especially in North Africa) | least concern but decreasing population trend |
| European Turtle-Dove / *Streptopelia turtur* | farmland, wide variety of woodland types, steppe, semi-desert, hedges, borders of forests, young tree plantations, woody marshes, does not breed close to towns or villages, breeding at low altitudes (<500 m) | Terrestrial | shrubs, lowest parts of trees, shrubs or hedges | Sahel-Sudan | granivorous, seeds, fruits of weeds and cereals, rarely also berries, fungi, invertebrates | April to September | less common | category 2: strongly at risk | occurs in Europe (25-49 % of global range), but not Scandinavia except South of Finland, parts pf middle East, Kazakhstan and Usbekistan, Northern Africa and a belt south of the sahara zone (Sahel-zone), decreasing trend due to change in agricultural practices and transformation of agricultural land, including destruction of hedges and scrubs | vulnerable, with decreasing population trend |
| Fieldfare / *Turdus pilaris* | farmland, part-wooded and part-open country, trees for breeding and roosting and hedges and open ground for foraging, boreal forests, scrub, clearings, parks and gardens, moorland and woodland edges | Terrestrial | trees | Westpalearctic | invertebrates, invertebartes and fruit, berries and seeds in winter, shoots and buds in spring | April to late August | common | not mentioned on red list of Brandenburg 2019 | occurs in the whole of Europe (40 % of the global range), Russia, Turkey, parts of northern Africa | Least concern, population trend is stable |
| Common Quail / *Coturnix coturnix* | farmland, open habitats including agricultural land (fields of clover, winter wheat, cereals, hay, rough grass, overgrown fallow) , areas with dense herb layers, avoids bare soils, trees and scrub | Terrestrial | ground-level | Sahel-Sudan, but can also winter as far north as UK and Germany or the Meditarranean  | insectivorous, seeds of grasses, weeds and grain, ground-dwelling invertebrates | mid-May to August | less common | not mentioned on red list of Brandenburg 2019 | occurs in Europe (40 % of global range), parts of Russia and Asia + India, parts of Middle East, Northern Afrcia, Sadelzone, parts of southern Africa | least concern but decreasing population trend |
| Meadow Pipit / *Anthus pratensis* | farmland, wide range of open habitat such as tundra, moorland, heathland, bogs, saltmarshes, dunes, coastal meadows, hillsides, forest clearings, fallow land and occasionally in arable land | Terrestrial, Freshwater, Marine | ground-level, concealed amongst vegetation | Westpalearctic | insectivorous, mainly invertebrates but consumes some plant seeds in autumn and winter | late March to August | less common | category 2: strongly at risk | occurs in Europe (75 - 94 % of global range), also in northern part up to south eststern Greenland, parts of Russida, Kaskhstan, parts of Middle East and Northern Africa | near Threatened with decreasing population trend |
| Western Yellow Wagtail / *Motacilla flava* | farmland, damp or wet habitats with low vegetation: damp meadows, marshes, waterside pastures, sewage farms and bogs, damp steppe and grassy tundra, large forest clearings | Terrestrial, Freshwater | ground-level | Sahel Sudan | insectivorous, terrestrial and aquatic invertebrates, some plant material and especially seeds | April to August | common | not mentioned on red list of Brandenburg 2019 | occurs in Europe, parts of Russia, Turkey | least concern but decreasing population trend |

# A 2. Agriculture

We estimated the potential agricultural net returns per square kilometer with the online tool for farmers provided by the “Agricultural Advisory Board for Engineering and Building” (Batáry et al., 2017; Kirchweger et al., 2020; *Leistungs-Kostenrechnung Pflanzenbau*, n.d.). The tool can be accessed at <https://daten.ktbl.de/dslkrpflanze/postHv.html#Auswahl> (in German). This online tool allowed us to calculate potential net returns for several crop types on the basis of several input variables, such as crop type, machinery, field size, fertility and soil type, distance to the farm, fertilizer inputs, and tillage practice and separately for organic and conventional farming. The calculation within the tool multiplies the assumed market price for each crop with the expected yields, resulting in the total revenue in euro per hectare. From this, we subtracted the expected direct costs for fuel, fertilizer, pesticides, and insurance payments as well as expected variable costs (e.g., for machinery). We calculated the net returns by subtracting the fixed costs from the total revenue per crop and hectare. We followed these steps for the 14 main crop types in the study region, which in total represent about 90% of the cropland area. It is infeasible to parametrize the tool for the other 10% of the crops because the tool does not contain every possible crop. Therefore, for the other 10% of crop types, we assumed average values obtained by grouping the data by organic/conventional, field size, a combination of yield and soil type, mechanization, and distance to the farm and calculating the average operating net return per group.

To obtain values for the entire study region, we calculated the share of each crop for each landscape grid cell and each farm (6034 farms in 2018). This resulted in a four-dimensional array containing values in square meters for each crop and each farm. This takes the form of 6034, 14, 250, 250, where 6034 is the number of farms, 14 the number of crop types, and 250\*250 the extent of the landscape raster. We then estimated the average plot size of the grid cells of each landscape and reclassified the soil quality map into three classes of low (< 30), medium (30–50), and high (> 50) soil quality. We derived information about organic or conventional management at the farm level from the Integrated Administration and Control System (IACS). As the IACS data do not contain the farmstead location, we estimated the distance of fields to the farmstead by calculating the average minimum distance of the fields of that farm to all other fields of that farm. This information was then used to parametrize the net returns calculator for the following crop types: grassland, maize for biogas, maize, winter wheat, rapeseed, barley, winter rye, summer oat, winter triticale, arable grass, clover-alfalfa, clover grass, and sunflowers.

Doing this for the years 2017, 2018, and 2019 and averaging the net returns resulted in a map showing the average net returns per agricultural landscape (Figure S2).

To obtain values for all possible transitions into other agricultural landscapes, the average field size and the total agricultural area were adapted, caused by the introduction/removal of woody features. Then, the process described above was repeated with these new values, which resulted in a total of four values per agricultural landscape. The change was based on the average value of all agricultural landscapes (Main Text Figure 1) for average field sizes and the proportion of woody features. It was assumed that all farms and crop types gain or lose area equally within that agricultural landscape.



Figure S2. Potential agricultural net returns averaged for the years 2017, 2018, and 2019.

# A 3. Formulation of the optimization problem

We defined the frontier as a mixed integer linear programming problem. This maximizes the farmland bird biodiversity objective function while the agricultural net returns target is gradually decreased. We obtain the maximum potential agricultural net returns target in a first iteration by maximizing agricultural production without considering the biodiversity objective function. Then, the objective function maximizes biodiversity metric *B* and is subject to several constraints:

Maximize: $\sum\_{s=1}^{S}B\_{s}$

Subject to: $\sum\_{j=1}^{J}\sum\_{i=1}^{I}a\_{ij} x\_{ij} \geq A\_{t}$

$B\_{s}=\sum\_{j=1}^{J}\sum\_{i=1}^{I}x\_{ij} z\_{sj} u\_{si}$

$B\_{s} \geq frac\*init\_{s} ∀s \in S $

$\sum\_{j=1}^{J}x\_{ij}=1 ∀i \in I$

$x\_{ij} \in \left\{0,1\right\}$

$x\_{ij}=1, j \in J\_{T1}$

$$frac \in \{0, 0.7\}$$

$B\_{s}$ = biodiversity metric for bird species *s* being considered

xij = a binary decision variable allocating cell *i* into landscape type *j*.

aij = agricultural net returns for cell *i* and landscape *j*

At = the overall agricultural net returns and *t* are the respective targets, which are degraded iteratively to depict the Pareto frontier

zsj = relative abundance of species *s* for landscape *j*

usi = probability of occurrence of species *s* for cell *i*

inits = the aggregated relative abundance for the entire study area of species *s* for the initial landscape map

*B* is the biodiversity metric, which is the summed product of the relative abundance of species *s* for landscape *j* at cell *i* and the probability of occurrence of cell *i* for species *s*. Depending on the scenario, *frac* is either 0 for the “No constraints” scenario or 0.7 for the “Small input, big gain” scenario. $init\_{s}$ is the aggregated relative abundance for the entire study area of species s for the initial landscape map. The constraint is either not active if *frac* = 0 or limits the maximum decline per species to 70% of the initial value (so the maximum decline is 30%). The aggregated agricultural net returns aij for all cells *i* and all landscapes *j* need to be greater or equal to the overall agricultural net returns target At, which is being iteratively degraded. If landscape j is an element of Jt1 (all stable landscapes, i.e., forest, water, urban, other), xij = 1. This constraint ensures that these landscapes remain stable.

# Literature

Batáry, P., Gallé, R., Riesch, F., Fischer, C., Dormann, C. F., Mußhoff, O., Császár, P., Fusaro, S., Gayer, C., Happe, A. K., Kurucz, K., Molnár, D., Rösch, V., Wietzke, A., & Tscharntke, T. (2017). The former Iron Curtain still drives biodiversity-profit trade-offs in German agriculture. *Nature Ecology and Evolution*, *1*(9), 1279–1284. https://doi.org/10.1038/s41559-017-0272-x

EEA. (2019). *Copernicus Land Monitoring Service –High Resolution Layer Small Woody Features –2015 reference year. Product Specifications & User Guidelines.* https://land.copernicus.eu/user-corner/technical-library/hrl \_lot5\_d5-1\_product-specification-document\_i3-4\_public-1.pdf

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302–4315. https://doi.org/10.1002/JOC.5086

*IUCN Red List of Threatened Species*. (n.d.). Retrieved May 9, 2022, from https://www.iucnredlist.org/

Johnston, A., Hochachka, W. M., Strimas-Mackey, M. E., Ruiz Gutierrez, V., Robinson, O. J., Miller, E. T., Auer, T., Kelling, S. T., & Fink, D. (2021). Analytical guidelines to increase the value of community science data: An example using eBird data to estimate species distributions. *Diversity and Distributions*, *27*(7), 1265–1277. https://doi.org/10.1111/DDI.13271

Kamp, J., Frank, C., Trautmann, S., Busch, M., Dröschmeister, R., Flade, M., Gerlach, B., Karthäuser, J., Kunz, F., Mitschke, A., Schwarz, J., & Sudfeldt, C. (2021). Population trends of common breeding birds in Germany 1990–2018. *Journal of Ornithology*, *162*(1), 1–15. https://doi.org/10.1007/s10336-020-01830-4

Kass, J. M., Muscarella, R., Galante, P. J., Bohl, C. L., Pinilla-Buitrago, G. E., Boria, R. A., Soley-Guardia, M., & Anderson, R. P. (2021). ENMeval 2.0: Redesigned for customizable and reproducible modeling of species’ niches and distributions. *Methods in Ecology and Evolution*, *12*(9), 1602–1608. https://doi.org/10.1111/2041-210X.13628

Kass, J. M., Vilela, B., Aiello-Lammens, M. E., Muscarella, R., Merow, C., & Anderson, R. P. (2018). Wallace: A flexible platform for reproducible modeling of species niches and distributions built for community expansion. *Methods in Ecology and Evolution*, *9*(4), 1151–1156. https://doi.org/10.1111/2041-210X.12945

Kirchweger, S., Clough, Y., Kapfer, M., Steffan-Dewenter, I., & Kantelhardt, J. (2020). Do improved pollination services outweigh farm-economic disadvantages of working in small-structured agricultural landscapes? – Development and application of a bio-economic model. *Ecological Economics*, *169*, 106535. https://doi.org/10.1016/j.ecolecon.2019.106535

Kosicki, J. Z. (2021). The impact of feral domestic cats on native bird populations. Predictive modelling approach on a country scale. *Ecological Complexity*, *48*, 100964. https://doi.org/10.1016/J.ECOCOM.2021.100964

Landesamt für Umwelt (LfU). (2019). Rote Liste Brutvögel. *Naturschutz Und Landschaftspflege in Brandenburg - Beilage Zu Heft 4* .

Law, E. A., Macchi, L., Baumann, M., Decarre, J., Gavier-Pizarro, G., Levers, C., Mastrangelo, M., Murray, F., Müller, D., Piquer-Rodriguez, M., Torres, R., Wilson, K. A., & Kümmerle, T. (2021). *Fading opportunities for mitigating agriculture-environment trade-offs in a South American deforestation hotspot*. 1–34. https://doi.org/10.17605/OSF.IO/5EJCQ

*Leistungs-Kostenrechnung Pflanzenbau*. (n.d.). Retrieved January 11, 2022, from https://daten.ktbl.de/dslkrpflanze/postHv.html

Merow, C., Smith, M. J., & Silander, J. A. (2013). A practical guide to MaxEnt for modeling species’ distributions: what it does, and why inputs and settings matter. *Ecography*, *36*(10), 1058–1069. https://doi.org/10.1111/J.1600-0587.2013.07872.X

PECBMS. (2018). *European wild bird indicators, 2018*. https://pecbms.info/european-wild-bird-indicators-2018-update/

Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., & Blair, M. E. (2017a). Opening the black box: an open-source release of Maxent. *Ecography*, *40*(7), 887–893. https://doi.org/10.1111/ecog.03049

Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., & Blair, M. E. (2017b). Opening the black box: an open-source release of Maxent. *Ecography*, *40*(7), 887–893. https://doi.org/10.1111/ECOG.03049

Radosavljevic, A., & Anderson, R. P. (2014). Making better Maxent models of species distributions: complexity, overfitting and evaluation. *Journal of Biogeography*, *41*(4), 629–643. https://doi.org/10.1111/JBI.12227

R Core Team. (2021). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing. https://www.R-project.org/

Sullivan, B. L., Wood, C. L., Iliff, M. J., Bonney, R. E., Fink, D., & Kelling, S. (2009). eBird: A citizen-based bird observation network in the biological sciences. *Biological Conservation*, *142*(10), 2282–2292. https://doi.org/10.1016/J.BIOCON.2009.05.006

Svensson, L., Mullarney, K., & Zetterström, D. (2017). *Der Kosmos Vogelführer: Alle Arten Europas, Nordafrikas und Vorderasiens* (3rd ed.). Kosmos.

Torres, R., Kuemmerle, T., & Zak, M. R. (2020). Changes in agriculture-biodiversity trade-offs in relation to landscape context in the Argentine Chaco. *Landscape Ecology*, *0123456789*. https://doi.org/10.1007/s10980-020-01155-w

Wolff, S., Hüttel, S., Nendel, C., & Lakes, T. (2021). Agricultural Landscapes in Brandenburg , Germany : An Analysis of Characteristics and Spatial Patterns. *International Journal of Environmental Research*. https://doi.org/10.1007/s41742-021-00328-y